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Control of tin compositon and mold medium to reduce the severity of microshrinkage in copper-tin sand catings

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Control of Tin Composition and Mold Medium to Reduce the Severity of Microshrinkage in Copper-Tin Sand Castings

by
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Thesis Advisor

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABSTRACT

Microshrinkage is a common solidification defect that negatively impacts mechanical properties and pressure tightness. It is therefore important that the fraction of microshrinkage be minimized and its distribution maximized. Quantitative Image Analysis data is produced to explain the interactive effect of tin composition and mold medium on the severity of microshrinkage in copper-tin alloys. Data is generated for a variety of copper-tin alloys ranging in tin composition from 10.5 to 22 wt%. Each composition is cast for both silica sand and steel chill mold mediums. The steel mold is used to simulate the effect of localized chilling. Localized chilling is a common method of increasing solidification rate in sand castings. The severity of microshrinkage is found to be low for all tin compositions when chill mold condition is applied. The optimum condition is identified as 22 wt% Sn cast in a chill mold. For sand mold condition, the highest severity of microshrinkage is identified at 10.5 wt% Sn and the lowest severity is 22 wt% Sn. Control of tin composition and mold medium are found to be highly effective methods of reducing the severity of microshrinkage in copper-tin sand castings.

I. INTRODUCTION

A. Background

The solidification of copper-base alloys is commonly categorized into two groups (modes) representing extremes of behavior.[1,2,3] Obviously, many alloys will fall into intermediate classification. The volume fraction of shrinkage is controlled by the mode of solidification. The solidification mode is a function of the degree of constitutional supercooling, which in turn is controlled by the actual solidification range. The actual solidification range is controlled by the equilibrium solidification range and thermal conditions.

Mode 1 solidification initiates by crystallite formation on the mold walls. Once the temperature adjacent to the mold wall drops below the liquidus temperature, crystals grow and link with neighbors to form a continuous skin of solid metal (solidification front). The solidification front advances perpendicular to the mold wall into the interior of the casting. Mode 1 behavior is illustrated in figure 1.[4,5] The solidification front shrinkage in Mode 1 alloys is continuously fed by the adjacent liquid metal. The absence of adjacent liquid metal reserve will result in the formation of shrinkage. Mode 1 shrinkage will appear as pronounced smooth walled cavities. Gating which promotes directional solidification and incorporates adequate riser feeds will effectively eliminate Mode 1 shrinkage.

Mode 2 solidification begins on the mold walls. However, it is immediately retarded since the crystallites initially solidified are poorer in alloying elements than the liquid from which they solidified. Rejected solute from the crystallites enriches the surrounding liquid and thereby lowers the liquidus temperature. With further extraction of heat from the mold, the temperature of the surrounding liquid and the unaffected liquid nearer to the interior of the casting decreases. Since the liquidus temperature of the unaffected liquid is higher than that of the surrounding liquid, a second batch of crystallites nucleates outside the enriched area. This process repeats itself until small crystallites have nucleated throughout the casting. Solidification continues by the simultaneous growth of all the crystallites. After approximately 70% solidification is complete, crystals have grown large enough that they interlock with each other. The remaining liquid is now isolated in many pools throughout the casting. As the isolated pools solidify, there is no source of compensating metal. Therefore, Mode 2 solidification shrinkage forms in these locations. Directional solidification and risering will only slightly reduce the volume of shrinkage in Mode 2 castings. The work of Jackson illustrates this phenomena.[6] Mode 2 solidification is illustrated in figure 2 and behavior intermediate to Mode 1 and Mode 2 is shown in figure 3.[4,5] Mode 2 shrinkage is commonly referred to as microshrinkage and will henceforth be referred to as such.

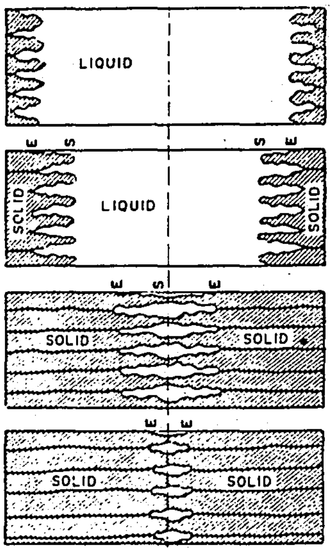


Figure 1. Mode 1 solidification. [4,5]

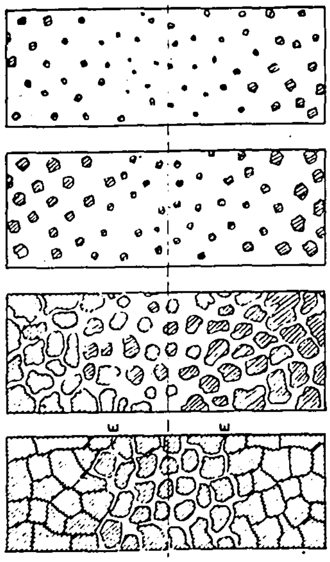


Figure 2. Mode 2 solidification. [4,5]

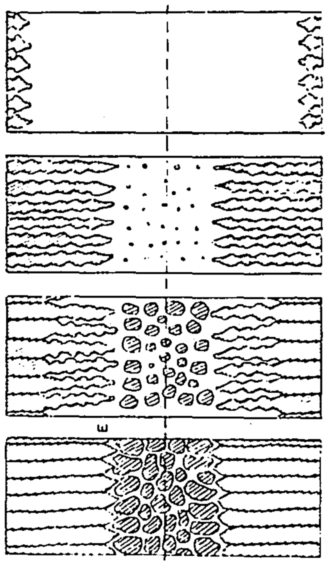


Figure 3. Intermediate solidification. [4,5]

When microshrinkage is concentrated, interconnection can extend through the wall of a pressure vessel and allow leakage to occur. Interconnection will also cause reduced mechanical properties.[7,8] A large percentage of microshrinkage can have a good pressure tightness and mechanical properties if the microshrinkage is well dispersed, however a small percentage of microshrinkage can have poor pressure tightness and mechanical properties if the microshrinkage is not well dispersed. It is therefore important that the percentage of microshrinkage be minimized and the dispersion of MS be maximized. Interconnected and well dispersed microshrinkage are illustrated in figures 4 and 5 respectively. [9]

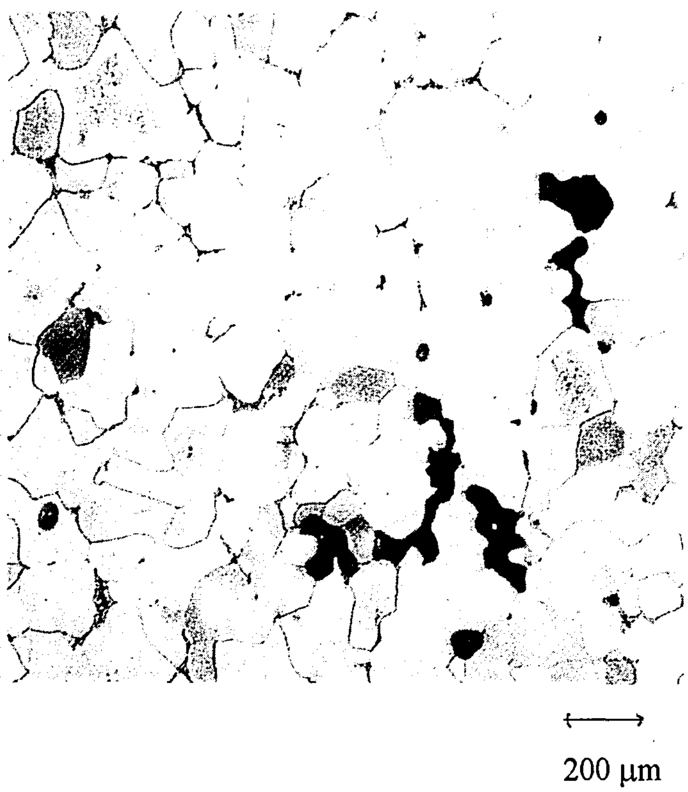


Figure 4. Interconnected Microshrinkage [9]

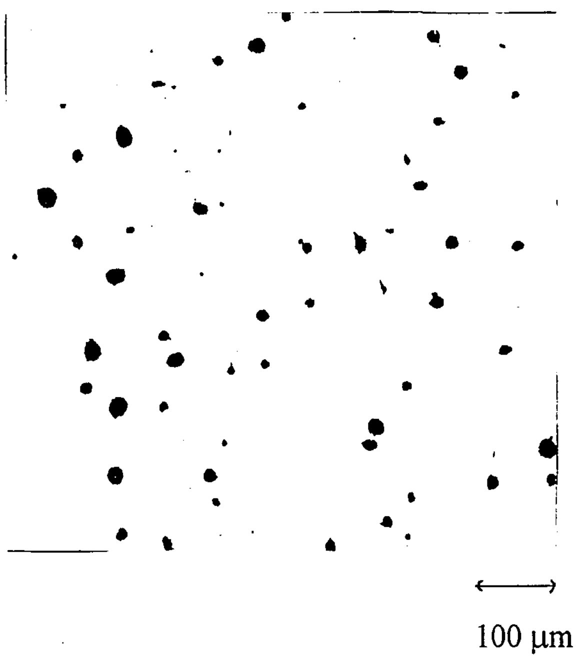


Figure 5. Dispersed Microshrinkage [9]

B. Objectives

Microshrinkage severity is a measure of the damaging effect of microshrinkage to mechanical properties and pressure tightness. It is calculated by dividing the average percentage of microshrinkage for each specimen (calculated from Quantitative Image Analysis data) by the average number of microshrinkage indications for each specimen (calculated from Quantitative Image Analysis data). These 3 factors will be referred to as MS severity, MS area%, and MS distribution. MS severity can only be reduced by designing the casting process against Mode 2 solidification and/or increasing the MS distribution. Chemical composition and mold medium are casting process variables that will influence MS severity. The chemical composition will establish the equilibrium solidification range and the mold medium will influence thermal conditions. Thermal conditions will also control MS distribution. This is important because MS severity can be significantly reduced if the microshrinkage is well dispersed. Specific information can only be attained by experimental testing for actual conditions. Experimental data of this sort are extremely rare. Evidence has been introduced by Winegard and Chalmers indicative that alloys which are cooled slowly enough to produce negligible concentration gradients commonly have Mode 1 solidification regardless of equilibrium solidification range.[10] Experimental data have been produced to show that alloys solidified extremely rapidly also have Mode 1 structures regardless of equilibrium solidification range[11].

This investigation produces Quantitative Image Analysis data to establish the interactive effect of mold medium and tin composition on microshrinkage in copper-tin sand castings. Analysis of this data will provide basic guidelines for reducing the percentage of microshrinkage and increasing the distribution of microshrinkage. Cu-Sn is an ideal binary system for this investigation because it displays a wide array of equilibrium solidification ranges. This is illustrated in the Cu-Sn equilibrium phase diagram shown in figure 6. Silica sand is a common mold medium for the sand casting process. Directional solidification within the mold is achieved by strategic insertion of steel chills into the silica sand matrix to initiate solidification at specific locations. Chills are blocks of a relatively high thermal conductivity material (relative to that of the sand matrix). It is therefore appropriate to select silica sand and carbon steel (1018) chill for the mold medium (cooling rate) conditions considered. Cooling is approximately 80 times more rapid in 1018 carbon steel than in silica sand. Thermal conductivity of 1018 carbon steel is approximately 51.0 W/m/K at 100 deg. C and that of silica sand is approximately .630 W/m/K at 100 deg. C. At 500 deg. C, the difference in cooling rate between these two mediums is slightly larger.

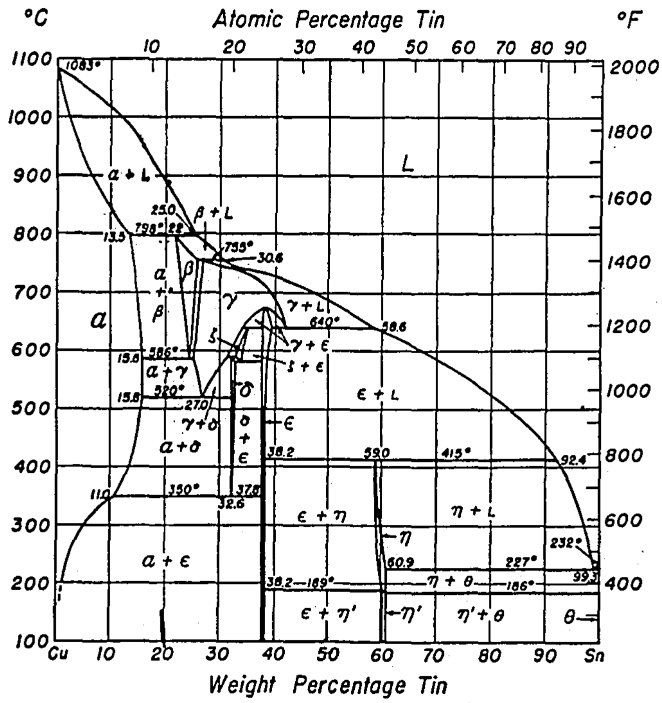


Figure 6. Cu-Sn equilibrium phase diagram

The Sn compositions selected are approximately 10.8, 14.0, 18.8, and 22.0 wt%. These compositions are selected because they span a wide range of equilibrium solidification ranges. Equilibrium solidification ranges for these compositions are approximately 190, 150, 100, and 50 deg. C. respectively. 8 specimens representing each of these 4 compositions combined with both mold mediums are cast. Quantitative

Image Analysis of these samples measures the average percentage of shrinkage per microscopic field and the average number of shrinkage indications per microscopic field (distribution). MS Percentage, MS Distribution, and MS Severity results are the basis for discussion of copper-tin casting design to reduce MS Severity by controlling tin composition and mold medium.

II. EXPERIMENTAL PROCEDURE

A. General

8 specimens representing four chemical compositions within the 10.5-22.0 wt% Sn range of the copper-tin binary system are produced. One specimen for each composition will represent steel chill mold cooling condition and one specimen for each composition will represent silica sand mold cooling condition. Tin composition/mold medium combinations are as follows (wt% Sn/mold medium): 10.5/sand, 14.0/sand, 18.8/sand, 22.0/sand, 10.5/chill, 14.0/chill, 18.8/chill, 22.0/chill. Analysis of Quantitative Image Analysis data establishes guidelines for design against microshrinkage in copper-tin alloys.

B. Chemical Analysis

Chemical composition is modified by tin or copper addition to Copper Alloy No. C91300 (81Cu/19Sn). This is accomplished by calculation based upon heat size and preliminary chemical analysis. Chemical analyses are performed with an ARL Optical Emission Spectrometer. Chemical analysis specimens are cast in a high thermal conductivity mold (310 Stainless Steel) to avoid segregation and consequential error in analysis. Each analysis is the average of 3 separate analyses taken from different locations on the chemical analysis specimen. A calculation is made based upon the predicted chemistry of the alloy to determine the initial charge. After melting of the initial charge, a preliminary analysis is taken. Modifications to the initial charge are based upon this preliminary analysis. A final chemical analysis is taken after modifications are made. All chemical modifications are made at 1090 deg. C. In addition to copper and tin, the following trace elements are analyzed for: Pb, Zn, Fe, Sb, Ni, S, P, Al, Si, Co.

C. Mold Medium

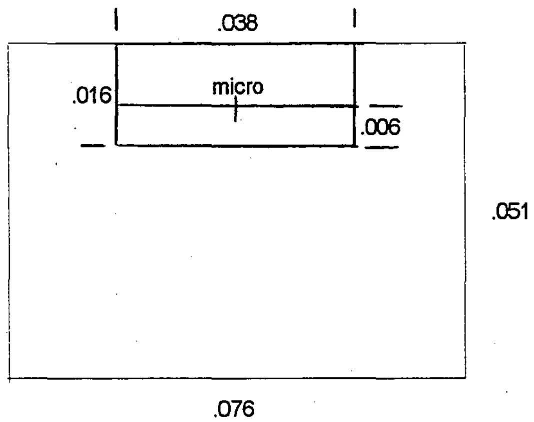
Mold mediums are as follows:

Sand: Chemically bonded silica sand

Chill: 1018 Carbon Steel

D. Specimen and Mold Design

Specimen and mold design are illustrated in Figure 7. All horizontal lines are diameters (the specimen is cylindrical in shape). The mold is .076 m diameter and .051 m thick. The specimen is .038 m diameter and .016 m thick. The specimen is prepared on the plane set back .006 in figure 7. Data is taken from the center of this plane (identified in figure 7 by the intersection of this plane with a small vertical line adjacent to "micro").



unit = meter

Figure 7. Specimen design.

E. Melting and Pouring

All melting and pouring variables are held constant for all specimens. Metal is melted in an electric induction furnace and heated to a maximum temperature of 1120 degrees C. Metal is poured at this temperature. Mold temperature at the time of pouring is room temperature.

F. Specimen Preparation For Microstructural Analysis

Specimens are prepared for examination in the area described in IId. This region is common for all 8 specimens. Microshrinkage is most clearly revealed unetched. One specimen is presented in the etched condition to display the lesser clarity of microshrinkage compared with the unetched condition. Etching is performed with a solution consisting of equal parts of NH_40H, H_2O, and H_20_2.

G. Optical Microscopic Examination

Photomicrographs of 8 specimens are taken at 200X magnification. These photomicrographs are used as a visual aid in conjunction with Quantitative Image Analysis Data to analyze microshrinkage severity.

H. Quantitative Image Analysis

A LECO 2001 Quantitative Image Analysis System is used to measure the percentage of MS and the number of MS indications for each of 25 fields. The major source of error in this technique is specimen preparation. Smearing of microshrinkage during polishing can result in partial closing of microshrinkage indications. In brittle materials, decohesion can cause microshrinkage enlargement.[12] Accurate estimation of the error in Quantitative Image Analysis data is not possible since polishing quality has an overwhelming influence on data and measurement of pore distortion is not possible. With careful polishing technique, the prediction for error in Quantitative Image Analysis data is low.

I. Calculation of MS area%, MS distribution, and MS severity from Quantitative Image Analysis data.

Calculations are as follows:

MS area% = average MS area% for all 25 fields considered.

MS distribution = average MS distribution for all 25 fields considered.

MS severity = MS area% divided by MS distribution.

III. RESULTS AND DISCUSSION

A. General

MS area%, MS distribution, and MS severity as calculated from the Quantitative Image Analysis data located in the Appendix (tables 3-10) are summarized in Table 1. The equilibrium solidification ranges shown in Table 1 were extrapolated from the equilibrium phase diagram (figure 6). Tin compositions are taken from the chemical analyses shown in table 2. Chemical analyses for sand and chill mold specimens for a given composition are identical since both specimens were cast from the same heat of metal. Elements other than copper and tin account for less than .2% of the total composition in all 4 cases. This minimizes the potential for sources of error in this area. Although MS severity is used to quantify the damaging effect of shrinkage, MS area%, and MS distribution results must be considered since these factors control MS severity.

Table 1. MS area%, MS distribution, and MS severity data summary

tin composition (wt%)	equilibrium solid. range (degrees C)	mold medium	MS area%	MS distribution (#/area)	MS severity (MS area%/ MS distr.)
22	50	sand	0.35	8.2	0.043
18.8	100	sand	0.84	9.28	0.091
14	150	sand	1.57	12.84	0.122
10.5	190	sand	7.78	8.6	0.905
22	50	chill	0.56	57.12	0.01
18.8	100	chill	0.42	30.08	0.014
14	150	chill	1.63	48.92	0.033
10.5	190	chill	1.69	93.64	0.018

Table 2. Chemical analyses for the 10.5,14,18.8, and 22 wt% Sn specimens

Element	10.5 wt% Sn	14 wt% Sn	18.8 wt% Sn	22 wt% Sn
Cu	89.2	85.872	85.872	77.774
Sn	10.52	14.012	18.786	21.984
Pb	0.04	0.021	0.043	0.052
Zn	0.05	0.02	0.038	0.059
Fe	0.04	0.003	0.001	0.028
Sb	0	0.014	0.017	0.02
Ni	0.08	0.035	0.057	0.06
S	0	0.007	0.011	0.01
P	0.02	0.001	0.002	0.003
Al	0	0.006	0.002	0.002
Si	0	0.005	0.005	0.006
Co	0	0.005	0.004	0.003

B. *MS distribution*

Graphic representation of MS distribution as a function of tin composition is shown in figure 8. Photomicrographs for each of the 8 specimens are shown in figures 9-17. The poor polishing quality of the 10.5 wt% Sn specimen cast in a sand mold specimen is the result of high MS area% combined with low MS distribution. Large microshrinkage indications interfere with the polishing tool and cause scratching. Two photomicrographs of the 18.8 wt% Sn chill mold specimen (one etched and the other unetched) are included to display the problem created by etching (figures 14 and 15). Many of the smaller microshrinkage indications blend into microstructural features revealed by etching, therefore when observing microshrinkage, the unetched condition is preferred. MS distribution for the chill mold is significantly larger than that for the sand mold for all compositions considered due to increased undercooling in the chill mold case. The parabolic shape of the chill mold curve can be explained by the interaction of 3 factors. One factor is that faster cooling should narrow the solidification range and move the solidification mode toward mode 1 (larger columnar grains). Secondly, faster cooling should increase the number of nucleation sites due to larger undercooling and thereby increase the number of grains. Finally, as tin composition increases within the range considered, equilibrium solidification range decreases. This will promote mode 1 solidification and larger grains. Relative to the chill mold results, MS distribution for the sand mold is low and nearly constant with variable tin composition.

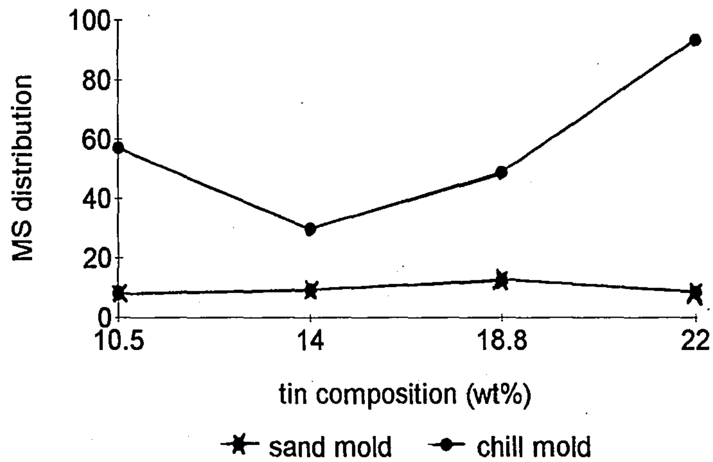
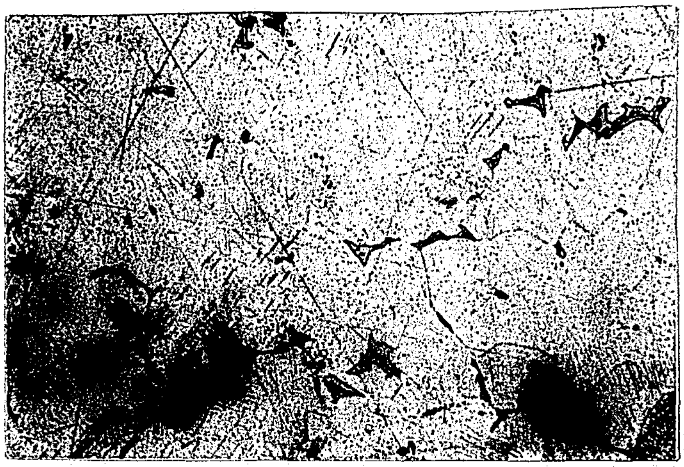


Figure 8. MS distribution as a function of tin composition. Units for MS distribution are number of indications per Quantitative Image Analysis field area.

The chill mold results shown in figure 8 demonstrate that between approximately 10.5 and 14 wt% Sn MS distribution decreases sharply, and between 14 and 22 wt% Sn it increases sharply. This is indicative that between 10.5 and 14 wt% Sn, undercooling effects diminish relative to the effects of narrowing of the solidification range. Between 14 and 22 wt% Sn, the effects of narrowing of the solidification range diminish relative to undercooling effects. For the case of sand mold medium, MS distribution is consistently low within the entire range of wt% Sn considered. This is the result of slower cooling. A small increasing trend is observed between 10.5 and 18.8 wt% Sn and a small decreasing trend from 18.8 to 22 w.% Sn. The increase is unexpected since decreasing solidification range with increasing tin content should shift the solidification mode behavior toward mode 1 and thereby decrease the number of nucleation sites. However, since this rate of increase is relatively small, its accuracy must be questioned since there are many potential sources of error. The effect of mold medium on MS distribution is obvious in photomicrographs where MS percentage is not extremely low. This is the case in figures 9 through 14. The distribution effect becomes less obvious as solidification range narrows and MS percentage decreases (see figures 16 and 17). Optimum MS distribution within the range of specimens considered is clearly 22 wt% Sn solidified in a chill mold. Sand mold cooling for all tin compositions considered produces poor distribution results. Therefore within this compositional range, chill insertion into a sand mold is always effective to increase MS distribution and thereby reduce MS severity.

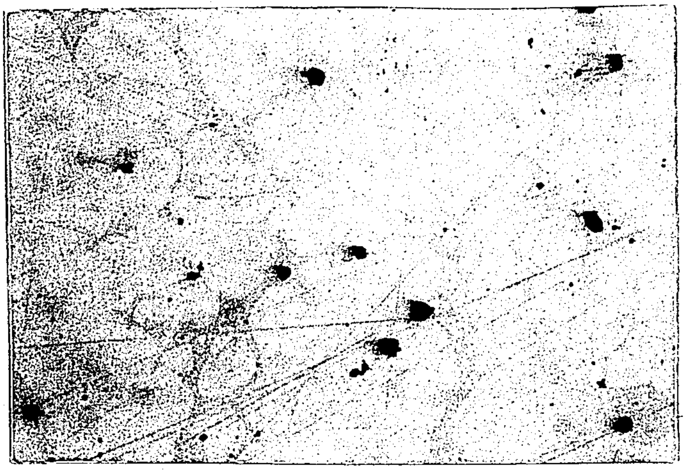


50 μm

Figure 9. 10.5 wt% Sn cast in a sand mold. Scratches are the result of polishing difficulty due a high MS severity.

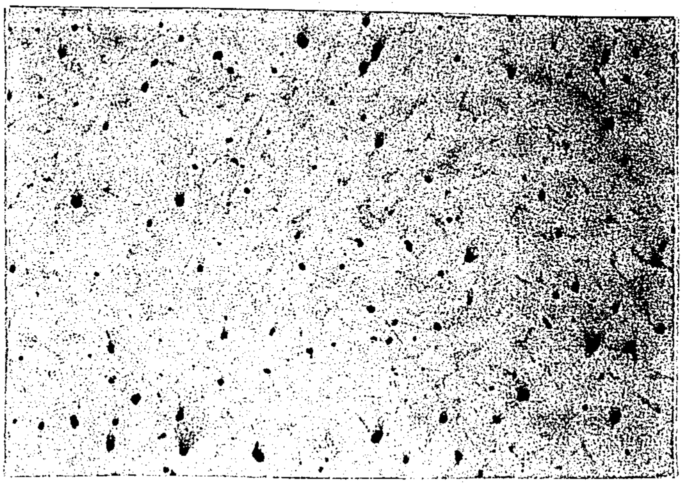
50 μm

Figure 10. 10.5 wt% Sn cast in a chill mold.



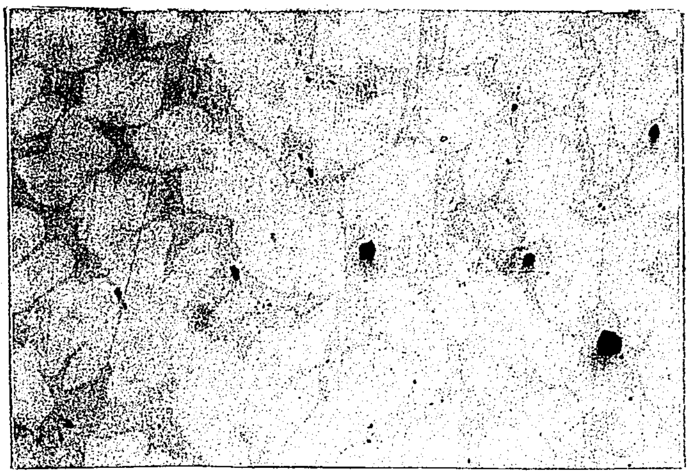
50 μm

Figure 11. 14 wt% Sn cast in a sand mold.



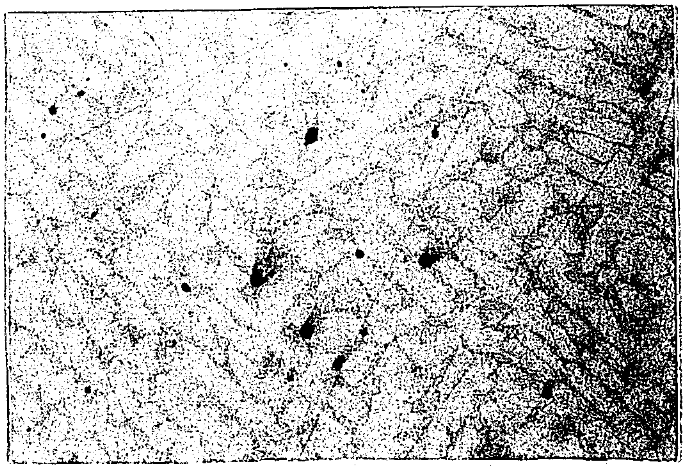
50 μm

Figure 12. 14 wt% Sn cast in a chill mold.



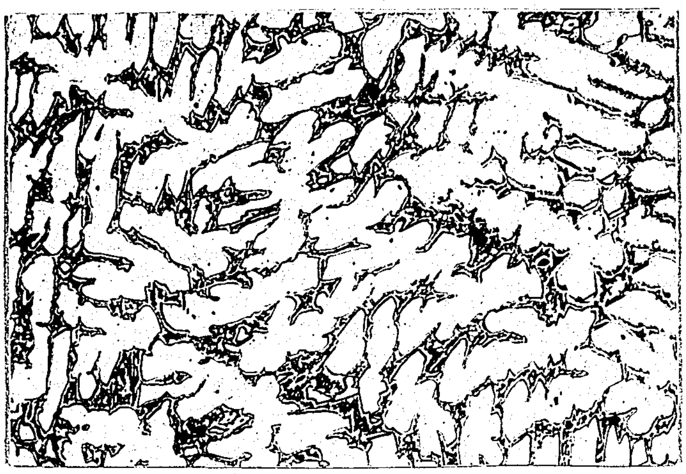
50 μm

Figure 13. 18.8 wt% Sn cast in a sand mold.



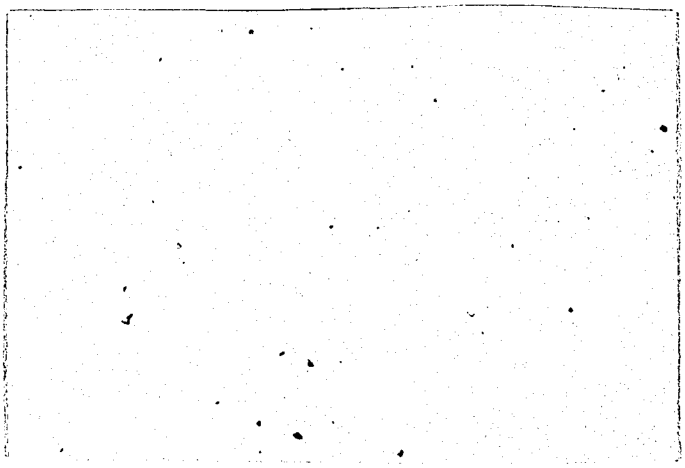
50 μm

Figure 14. 18.8 wt% Sn cast in a chill mold.



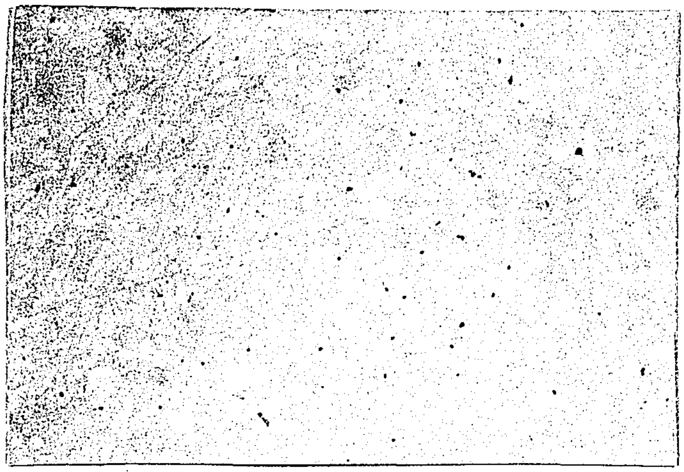
50 μm

Figure 15. 18.8 wt% Sn cast in a chill mold (etched). Microshrinkage is hidden by grain structure. Compare with unetched figure 14 (18.8 wt% Sn chill mold unetched).



50 μm

Figure 16. 22 wt% Sn cast in a sand mold.



50 μm

Figure 17. 22 wt% Sn cast in a chill mold. Lowest MS Severity (optimum condition of those tested).

C. MS area%

MS area% as it relates to tin composition is shown in figure 18 and in corresponding photomicrographs (figures 9 through 17). Within the 10.5 to 14 wt% Sn range of composition, MS area% for the sand mold decreases sharply (7.78 to 1.57). Mode 2 solidification behavior diminishes rapidly for the sand mold case through this interval. A small decreasing trend is observed for the chill specimen within this interval. MS area% for both the sand and chill mold specimens are approximately equal at 14 wt% Sn. Therefore, chill molding is an effective method of reducing MS area% when tin composition is between 10.5 and 14 wt% Sn. This contrast in behavior is clearly visible by comparison of figures 9 through 12.

For tin compositions greater than 14 wt.%, MS area% is relatively low for both mold mediums and the chill mold effect on solidification mode is small. MS area% is similar for both mold mediums within the range 14 and 22 wt% Sn. The only noticeable difference in behavior within this region is that MS area% for the chill mold decreases slightly more rapidly and then levels off, while MS area% for the sand mold decreases more slowly at a nearly constant rate approaching near to the MS area% at which the chill mold leveled off. Optimum MS area% within the compositional range considered occurs between 18.8 and 22 wt% Sn for both mold conditions. The highest MS area% is found at 10.5 wt% Sn for the sand mold. Since MS area% for the sand mold far exceeds MS area% for the chill mold throughout most of the 10.5 to 14 wt% Sn interval, tin composition within this range should be avoided when good pressure tightness and maximum mechanical properties are required. If tin composition within this range is unavoidable, chills should be inserted into the mold in critical areas.

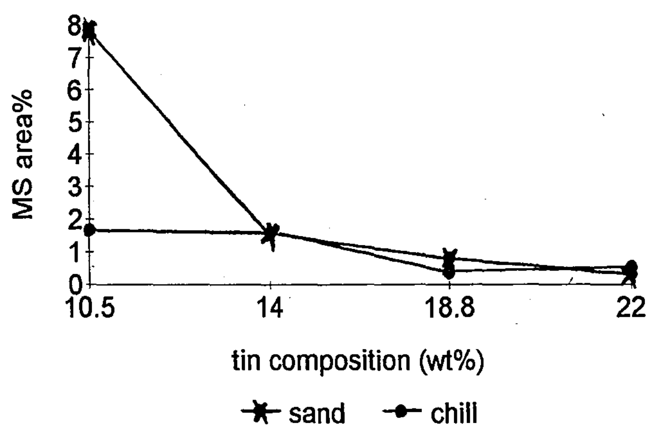


Figure 18. MS area% as a function of tin composition

D. MS Severity

The relationship between MS severity and tin composition is illustrated in figure 18 and corresponding photomicrographs are shown in figures 9-17. The polishing problem created by the high MS severity in the case of 10.5 wt% Sn sand mold is eliminated by substitution of a chill mold for the sand mold (see figure 10). The large difference in MS severity at 10.5 wt% Sn chill mold is the result of high MS area% and low MS distribution in the case of the sand mold, and moderate MS area% and high MS distribution in the case of the chill mold.

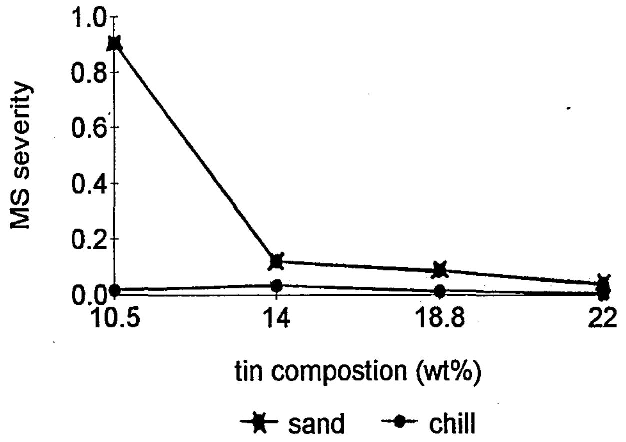


Figure 19. MS severity as a function of wt% Sn. Units for MS severity are MS area% / MS distribution

Solidification mode behavior for chill and sand mold becomes gradually more similar as the composition approaches 14 wt% Sn. Although chill mold MS severity is low throughout the 10.5 to 14 wt% Sn interval, there is a steep drop in MS severity for the sand mold case. This is primarily the result of a large decrease in MS area% which overshadows a decrease in MS distribution. Solidification mode within this interval is progressing toward mode 1. Copper-tin alloy selection within this interval of tin composition should be avoided if possible where good mechanical properties and pressure tightness are required, unless chills can be applied to critical locations to narrow solidification range and increase MS distribution.

MS Severity in the case of 14 wt% Sn is shown in figures 11 and 12 for sand and chill molds respectively. MS Severity in the case of the sand mold has been reduced enough to eliminate the scratches visible in the 10.5 wt% Sn case (see figure 11). MS severity slowly declines throughout the interval between 14 and 18.8 wt% Sn for both cases (see figures 11 through 15). Through the 18.8 to 22 wt% Sn interval, MS severity for chill and sand molds approach each other. At 22 wt% Sn, MS Severity is similar for the two cases. This is obvious in figures 16 and 17, where few differences can be interpreted from the photomicrographs.

Although, MS severity is low for all tin compositions considered with the chill mold, optimum MS severity is found for the case of the 22 wt% Sn cast in a chill mold. MS distribution is low for the 22 wt% Sn cast in a sand mold and MS area% is also low. The combined effect of this is a low MS severity, since the percentage of microshrinkage is small enough that the impact of MS distribution is small. Similarly, in the case of 22 wt % Sn cast in a chill mold, narrow solidification range produces a low MS percentage. In this case, however, the MS distribution is high. This high distribution factor further reduces the MS severity.

The MS severity results are indicative that control of tin composition and mold medium are effective methods of reducing microshrinkage in copper-tin alloys. For example, if selection of an alloy similar in tin composition to 10.5 wt% is unavoidable, the casting designer should apply chills in critical locations to reduce MS severity. In cases where tin composition is greater than 14 wt%, the designer should not expect large improvement in mechanical properties and pressure tightness by application of chills. The reduction in MS severity offered by chill molding is suggestive that any decrease in mold thermal conductivity will reduce MS severity. Other possible mold substitutes for sand castings are zircon and chromite sand in place of silica sand. Thermal conductivity of zircon and chromite sands are higher than that of silica sand. Silica sand is the most common sand casting mold material since its cost factor is less than other sands. This higher cost factor must be considered in addition to the extra cost of insertion of the higher conductivity sand into the silica sand matrix. When steel chills are used, the added cost of making the chills and inserting the chills must be considered. Although 22 wt% Sn is identified as the preferred tin composition for reduction of microshrinkage of those compositions tested, the casting designer must consider that there are other property changes that come with the higher tin compositions considered. As tin composition increases ductility will decrease. Copper-tin alloys with tin composition near 22 wt% are extremely brittle. Furthermore, as tin composition increases, material cost factor increases.

The mold medium results suggest that other casting process variables which effect cooling conditions will effect microshrinkage severity. Sand chemistry (moisture content), melting and pouring temperatures are some such variables which should be considered. These variables were held constant in this work. Future work in this area should include variation in these and other casting process variables that effect cooling rate. Furthermore, the effect of variation in residual elements on microshrinkage in the copper-tin system should be considered. Residual elements were nearly constant throughout the range of specimens considered in this work. Furthermore, the results provide some insight into future work that might be done for other tin compositions within the copper-tin system and for other alloy systems.

IV. CONCLUSIONS

The interactive effect of tin composition and mold medium on microshrinkage in copper-tin sand castings was investigated. The following conclusions can be drawn from this work.

1. The optimum condition for distribution of microshrinkage (maximum number of microshrinkage indications per Quantitative Image Analysis field area) within the range of specimens considered is identified to be 22 wt% Sn cast in a chill mold. All tin compositions when combined with a sand mold were found to have poor distribution results. Distribution for all chill mold specimens far exceeds distribution for all sand mold specimens. Within the compositional range considered, significant increase in microshrinkage distribution can be achieved by chill insertion into a sand mold.
2. The optimum condition for area percentage of microshrinkage (minimum area percentage of microshrinkage) is found for tin compositions between 18.8 and 22 wt% for both chill and sand molds. Area percentage of microshrinkage is maximized at 10.5 wt% Sn for the sand mold. Tin compositions within the 10.5 to 14 wt% Sn range should be avoided when good pressure tightness (see pages 5 and 6) and maximum mechanical properties are required, unless chills can be inserted in critical locations within the sand mold.
3. Microshrinkage severity (the ratio of the area percentage of microshrinkage to the number of microshrinkage indications in a given Quantitative Image Analysis field area) is low for all tin compositions considered when a chill mold is used. The optimum condition for minimization of the severity of microshrinkage is identified

as a tin composition of 22 wt% cast in a chill mold. At this tin composition, the severity of microshrinkage for the sand mold condition is also low. Therefore, chilling has little effect on the microshrinkage severity level near 22 wt% Sn. As tin composition approaches 14 wt%, chilling becomes increasingly more effective to reduce microshrinkage severity. For tin compositions less than 14 wt% and approaching 10.5 wt%, chilling becomes significantly more effective to reduce microshrinkage severity. Tin compositions near 10.5 should be avoided unless chills can be applied in critical locations.

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VI. APPENDIX

The following tables include Quantitative Image Analysis field measurement data for each of the 8 specimens.

Table 3. Quantitative Image Analysis data (40x objective) for 10.5 wt.% Sn cast in a sand mold

Field Number	Number of Microshrinkage Indications	Field Area% Occupied by Microshrinkage
1	11	0.3975
2	17	0.1115
3	0	4.4
4	10	2.1676
5	6	4.1226
6	8	0.6122
7	12	0.4784
8	2	0.2815
9	14	2.4198
10	21	0.7926
11	11	1.2062
12	17	2.2052
13	6	0.355
14	3	37.6198
15	25	2.3554
16	7	0.9247
17	6	4.5238
18	17	0.7628
19	12	72.2014
20	15	45.2239
21	2	0.0764
22	4	2.5886
23	9	0.5317
24	4	7.0275
25	14	3.3176
Average	8.6	7.8682

Table 4. Quantitative Image Analysis data (40x objective) for 10.5 wt.% Sn cast in a chill mold

Field Number	Number of Microshrinkage Indications	Field Area% Occupied by Microshrinkage
1	125	1.6804
2	91	1.6962
3	99	2.0945
4	95	1.7404
5	67	1.4159
6	76	1.2611
7	80	1.8976
8	93	1.555
9	174	1.503
10	87	1.825
11	101	2.0632
12	165	2.1672
13	70	1.9373
14	60	1.5389
15	71	1.7792
16	77	1.5001
17	86	2.0495
18	136	2.2019
19	94	1.5088
20	69	1.1637
21	81	1.2458
22	72	1.3432
23	74	1.5657
24	66	1.2343
25	132	2.1944
Average	93.64	1.6869

Table 5. Quantitative Image Analysis data (40x objective) for 14 wt.% Sn cast in a sand mold

Field Number	Number of Microshrinkage Indications	Field Area% Occupied by Microshrinkage
1	18	1.0716
2	9	1.0291
3	15	1.7049
4	10	1.5059
5	5	0.4656
6	1	0.0376
7	11	0.2378
8	12	0.4297
9	17	1.1001
10	8	0.549
11	11	0.6634
12	14	0.8165
13	14	0.1771
14	11	0.8958
15	16	1.3833
16	3	0.1503
17	34	16.3397
18	8	0.7307
19	41	6.1164
20	12	0.8504
21	12	0.324
22	10	0.6155
23	11	0.9437
24	9	0.5432
25	9	0.4528
Average	12.84	1.5654

Table 6. Quantitative Image Analysis data (40x objective) for 14 wt.% Sn cast in a chill mold

Field Number	Number of Microshrinkage Indications	Field Area% Occupied by Microshrinkage
1	49	1.6627
2	40	1.737
3	41	1.9443
4	56	1.7115
5	46	1.3808
6	55	1.7333
7	35	1.3924
8	40	1.1038
9	41	1.1397
10	51	1.8658
11	51	1.4402
12	51	1.4407
13	34	4.4539
14	58	1.5884
15	50	1.3924
16	54	1.7395
17	44	1.2466
18	61	2.2795
19	57	1.5451
20	60	1.5884
21	48	1.6921
22	58	2.1573
23	44	1.7953
24	51	1.8782
25	48	1.806
Average	48.92	1.6286

Table 7. Quantitative Image Analysis data (40x objective) for 18.8 wt.% Sn cast in a sand mold

Field Number	Number of Microshrinkage Indications	Field Area% Occupied by Microshrinkage
1	8	0.1292
2	5	11.8014
3	6	0.1812
4	18	0.4669
5	4	0.4462
6	9	0.1816
7	4	0.2819
8	24	0.9139
9	13	1.0572
10	6	0.0384
11	10	0.1276
12	8	0.0999
13	6	0.026
14	9	0.1044
15	1	0.7232
16	8	0.1688
17	7	0.2378
18	12	0.8495
19	11	0.4417
20	13	0.2039
21	6	0.3401
22	12	1.3399
23	9	0.0392
24	8	0.3397
25	15	0.2522
Average	9.28	0.8317

Table 8. Quantitative Image Analysis data (40x objective) for 18.8 wt.% Sn cast in a chill mold

Field Number	Number of Microshrinkage Indications	Field Area% Occupied by Microshrinkage
1	13	0.5688
2	38	0.4062
3	35	0.2985
4	36	0.3364
5	30	0.2749
6	40	0.3955
7	43	0.2877
8	30	0.1404
9	23	0.2935
10	32	0.2956
11	26	0.1961
12	25	0.4987
13	26	0.1994
14	37	0.1544
15	29	0.1717
16	29	0.2386
17	21	0.5197
18	27	0.2122
19	28	0.5325
20	27	0.9825
21	20	0.7315
22	34	1.2289
23	25	0.0735
24	48	0.9461
25	30	0.4499
Average	30.08	0.4173

Table 9. Quantitative Image Analysis data (40x objective) for 22 wt.% Sn cast in a chill mold.

Field Number	Number of Microshrinkage Indications	Field Area% Occupied by Microshrinkage
1	30	0.4541
2	39	0.6869
3	36	0.2947
4	54	0.2427
5	42	0.3562
6	28	0.3443
7	50	0.6518
8	47	0.4945
9	77	0.5544
10	34	0.4012
11	260	1.9034
12	29	0.1907
13	31	0.5701
14	32	0.4974
15	32	0.2634
16	129	0.7979
17	20	1.2578
18	76	0.8685
19	25	0.4033
20	44	0.4954
21	11	0.1705
22	59	0.4
23	78	0.4958
24	59	0.5424
25	106	0.6844
Average	57.12	0.5609

Table 10. Quantitative Image Analysis data (40x objective) for 22 wt.% Sn cast in a sand mold

Field Number	Number of Microshrinkage Indications	Field Area% Occupied by Microshrinkage
1	12	0.303
2	16	0.2151
3	8	0.0809
4	5	0.0173
5	10	0.194
6	10	0.7026
7	4	0.5498
8	6	0.0301
9	6	0.8314
10	14	1.0258
11	9	0.6778
12	8	0.0516
13	12	0.1482
14	8	0.4978
15	4	0.2762
16	10	0.0925
17	8	0.0594
18	10	0.5156
19	5	0.0656
20	1	0.0429
21	8	0.9032
22	10	0.0708
23	13	1.1001
24	2	0.0248
25	6	0.0863
Average	8.2	0.3505

VITA

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